

# Memory Representations in Rewriting Logic Semantics Definitions

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30 March 2008

- 1 Overview and Motivation
- 2 SILF and Stacked Memory
- 3 KOOL and Garbage Collection
- 4 Conclusions

# Outline

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# Rewriting Logic Semantics

Rewriting logic semantics provides a powerful environment for language prototyping and design:

- Rewriting logic provides formalism for specifying language semantics
- K definitional style provides methods to model complex language features, such as jumps (goto, break, continue, exceptions) and dynamic method dispatch
- Tool support provides ability to try language features quickly by executing and analyzing programs directly in semantics

# Executability

Executability raises new questions that don't make sense with non-executable semantics, such as:

- How fast can programs be executed using the semantics?
- In what ways can features be modified to maintain equivalent behavior but improve performance?
- What changes to the semantics will improve analysis performance? Will these improve execution performance as well?

# The Importance of Performance

Execution performance can be critical for experimenting with language features – programs can quickly become too large (in code size, memory usage, etc) to evaluate in the semantics otherwise.

# Semantics Changes and Analysis Performance

Prior work focused on improving analysis performance by modifying language semantics:

- KOOL language modified to use *auto-boxing* (automatic conversion of scalars to objects where needed) and *memory pools* (shared and unshared)
- Auto-boxing improved execution and analysis performance: reduced number of method calls, use of memory, complexity of language operations
- Memory pools improved analysis performance: non-shared memory operations used equations, reduced state space size

More details in [HillsRosu07].

# Costs of Semantics Changes

Improving performance by modifying language semantics can come at a cost:

- Changes *believed* to be equivalent, but would need to do formal proof to show this to be the case
- Changes to language features break modularity, making it harder to reuse features in other languages
- “Performance-aware” definitions become more complicated
- Semantics of language features may not be best place for performance improvements – auto-boxing is an optimization, but moving it into semantics of message dispatch makes it part of the language feature



# Memory-Representation Optimization

- Memory representation part of language-independent definition, provides *interface* containing operations that allow features to interact with memory
- Often reused in other languages, so improvements could be leveraged in multiple definitions
- Use of interface to memory maintains modularity of language features, minimizing number of changes needed outside memory modules – i.e., improvements to memory representation need not change individual language features

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# SILF

- SILF is a basic imperative language – **S**imple **I**mperative **L**anguage with **F**unctions
- Includes many features found in imperative languages, including global variables and arrays
- Does not include some features which make memory management hard – no address capture, no dynamic memory allocation

# SILF: Flat Memory Model

- Original memory model was “flat” – memory represented as a single set of location/value pairs
- Memory never “cleaned up” – continues growing as new locations allocated

```

1  sorts StoreCell Store .
2  subsort StoreCell < Store .
3  op [_,_] : Location Value -> StoreCell .
4  op nil : -> Store .
5  op __ : Store Store -> Store [assoc comm id: nil] .
6
7  eq k(lookupLoc(L) -> K) store(Mem [L,V])
8    = k(val(V) -> K) store(Mem [L,V]) .
    
```

# Improving SILF Memory Performance

- Improving ACI matching performance during lookup should improve evaluation performance
- Key Idea 1: Only global locations and locations in current function (i.e., stack frame) are visible – restricting lookups to just these should improve performance
- Key Idea 2: Without address capture and pointers, addresses are not visible on function return, so it should be possible to discard allocated memory on returning

# Improving SILF Memory Performance

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Key ideas lead to use of “memory stacks”, similar to stack frames used in standard imperative and OO language implementations.

# Stacked Memory Model

- Memory represented as a stack of smaller stores
- Top of stack contains store for current function, bottom contains global store
- Stack frame contains location number of smallest location in its store, with visible locations  $\geq$  this in function store, locations  $<$  this in global store
- Function call pushes new frame, return pops top frame

```

1  sort StackFrame Stack .
2  subsort StackFrame < Stack .
3  op [_,_] : Nat Store -> StackFrame .
4  op nil : -> Stack .
5  op _,_ : Stack Stack -> Stack [assoc id: nil] .
  
```

## Stacked Memory Model: Example

|                   |
|-------------------|
| Stack frame for f |
| ...               |
| Globals           |

```
1 function f(x) begin
2   var y; // 1
3   y = g(3); // 2
4   return y
5 end
6
7 function g(x) begin
8   ... return x // 3
9 end
```

- Example shows memory layout at code location 1
- Global variables located in bottom frame
- Variables local to current function `f` in top frame



## Stacked Memory Model: Example

|                   |
|-------------------|
| Stack frame for g |
| Stack frame for f |
| ...               |
| Globals           |

```
1 function f(x) begin
2   var y; // 1
3   y = g(3); // 2
4   return y
5 end
6
7 function g(x) begin
8   ... return x // 3
9 end
```

- Code location 2 contains a function call
- New memory frame for g pushed onto top of stack
- Items in f no longer visible

## Stacked Memory Model: Example

|                   |
|-------------------|
| Stack frame for f |
| ...               |
| Globals           |

```
1 function f(x) begin
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3   y = g(3); // 2
4   return y
5 end
6
7 function g(x) begin
8   ... return x // 3
9 end
```

- Code location 3 contains a function return
- Memory frame for function g popped from stack
- Memory stack now structured the same as before the call

# Stacked Memory Model Interface

Lookups triggered by language features redirected to use stacks, maintaining same interface to memory:

```

1  eq k(lookupLoc(L) -> K) store(ST)
2    = k(val(stackLookup(L,ST)) -> K) store(ST) .
3
4  ceq stackLookup(loc(N),([Nb,Mem], ST)) = lvsLookup(loc(N),Mem)
5    if N >= Nb .
6
7  ceq stackLookup(loc(N),([Nb,Mem], ST, [Nb',Mem']))
8    = lvsLookup(loc(N),Mem')
9    if N < Nb .
10
11 eq lvsLookup(L,([L,V] Mem)) = V .
    
```

# Performance

|             | Standard (Flat) Memory Model | Stacked Memory Model |
|-------------|------------------------------|----------------------|
| Test Case   | Time (sec)                   | Time (sec)           |
| factorial   | 3.711                        | 0.747                |
| factorial2  | 1664.280                     | 11.245               |
| ifactorial  | 1.047                        | 0.978                |
| ifactorial2 | 43.861                       | 15.441               |
| fibonacci   | 29.014                       | 1.939                |
| qsort       | 111.623                      | 15.374               |
| ssort       | 21.557                       | 14.657               |

- factorial recursively calculates  $20!$ ,  $40!$ , ...,  $200!$ ; factorial2 recursively calculates  $1!$ ,  $2!$ , ...,  $200!$ ; ifactorial and ifactorial2 are iterative versions of factorial and factorial2, respectively; fibonacci recursively calculates fib of 1, 2, ..., 15; qsort and ssort each sort 2 arrays of 100 elements each

# Evaluation

- Clear improvement in performance in all cases
- Limited changes to put new model in place: 6 equations, dealing with function call/return or memory, were modified
- Similar changes should be useful for other languages with similarly constrained memory models
- Lack of support for languages that can return allocated memory limits usefulness – not applicable to all imperative languages

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# KOOL

- KOOL is a standard object-oriented language: **K**-based **Object-Oriented Language**
- Provides standard OO features: classes, methods, inheritance, dynamic dispatch, etc
- Includes memory features of languages like Java: references, dynamic allocation, no explicit memory deallocation

# KOOL: Flat Memory Model

- Like SILF, memory model is “flat”, using a finite map and never performing clean-up
- Unlike SILF, uses Maude MAP module versus custom set definition
- Memory usage in KOOL much higher than in SILF – KOOL is a “pure” OO language, i.e., all values are objects, all operations (even arithmetic) involve object creation and method invocation (call by value)



# Improving KOOL Memory Performance

- Use of references, ability to return newly-allocated objects rules out a solution similar to that in SILF

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- So, use a classic memory management solution: Garbage Collection (GC)

Goal: Add garbage collection to KOOL with minimal changes to the existing language definition.

# Garbage Collection in KOOL

- Mark/sweep collector: works well with circular structures, easy to define and reason about
- Runs in two steps:
  - Mark: Identify all reachable locations in memory
  - Sweep: Discard all unreachable (unmarked) locations

# Defining the Store for GC

```

1 protecting MAP{Location,ValueTuple} *
2   (sort Map{Location,ValueTuple} to Store) .
3
4 op [_,,_] : Value Nat Nat -> ValueTuple .
    
```

- Before, Store defined as a Map from Location to Value; now, defined as Map from Location to ValueTuple
- ValueTuple includes two flags, one marking the memory location as shared/unshared, the other used as the GC mark bit (we're interested in the second here)

# Triggering GC

- Triggering GC done using `triggerGC` computation item
- GC triggered after a predefined number of allocations
- Triggering sets the state component `ingc` to indicate GC has started
- In KOOL `triggerGC` used in allocation operations inside memory modules – no definitions of language features (method dispatch, etc) need to be changed

## Step 1: Initialization

- When GC triggered, all mark flags on memory set to 0 (not marked) to start
- `mem` state component renamed to `gcmem` – keeps rules/equations that modify memory from firing, since they will fail to match

## Step 2: Mark Root Locations

- First step in marking will find *root locations* (locations found directly in computation parts of state) and mark them (using `markLocsInSet`)
- Operations defined recursively to find roots in different state components, like:
  - `KStateLocs` finds root locations in state components
  - `MStackLocs` finds root locations in method stack
  - `KLocs` finds root locations in computation

```

1  ceq threads(KS) ingc(gcMarkRoots      ) gcmem(Mem
2    = threads(KS) ingc(gcMarkTrans(LS)) gcmem(markLocsInSet(Mem,LS))
3    if LS := KStateLocs(KS) .
4
5  eq KStateLocs(env(Env) TS) = ListToSet(envLocs(Env)) KStateLocs(TS) .
6  eq KStateLocs(k(K) CS) = KLocs(K) KStateLocs(CS) .
7  eq KStateLocs(mstack(MSTL) CS) = MStackLocs(MSTL) KStateLocs(CS) .
    
```



## Step 3: Mark Locations Reachable from Roots

- Once root locations have been marked, need to find all other reachable locations
- Example: computation may hold reference to an object; object may then reference other objects
- Iterative process: keep marking reachable locations until fixed point reached
- Uses `valLocs` operation to get locations held in a value (like locations of object references held in object fields)

## Step 4: Sweep

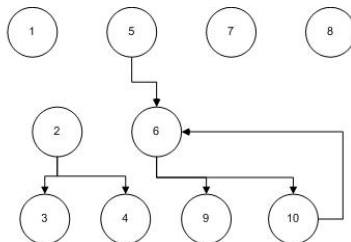
- Once iterative marking reaches a fixpoint, switch GC mode to sweep
- Sweeping is simple: all unmarked locations discarded
- When sweeping is complete, `gcmem` renamed to `mem` and allocation counter reset to 0 – GC is complete

```

1  eq ingc(gcSweep) gcmem(Mem) =
2    ingc(noGC(0)) mem(removeUnmarked(Mem)) .
3
4  eq removeUnmarked(_',_(L |-> [V,N,0], Mem))
5    = removeUnmarked(Mem) .
6  eq removeUnmarked(Mem) = Mem [owise] .
  
```

# GC Example

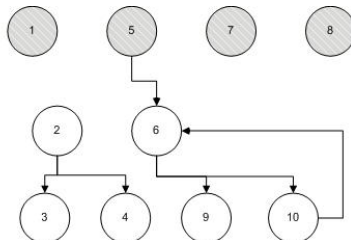
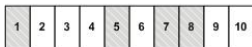
`k(... loc(1) ... loc(5) ... loc(8) ...) mstack(... loc(7) ...)`



- Graphic shows representation of K configuration
- `k` contains current computation, `mstack` contains the method stack, with most of the configuration elided
- Boxes numbered 1 through 10 represent memory locations
- Circles with numbers show which objects at which locations hold references to other objects

# GC Example

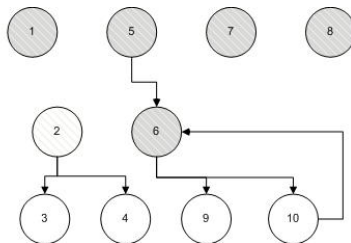
$k(\dots \text{loc}(1) \dots \text{loc}(5) \dots \text{loc}(8) \dots) \text{mstack}(\dots \text{loc}(7) \dots)$



- First part of mark step in GC marks roots
- Locations 1, 5 and 8 are present in  $k$
- Location 7 is referenced in the method stack (so it would be visible on method return)

# GC Example

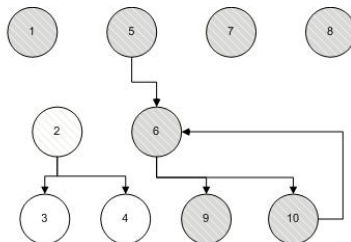
`k(... loc(1) ... loc(5) ... loc(8) ...) mstack(... loc(7) ...)`



- Next, see which locations are reachable from the roots
- First step discovers location 6 reachable from location 5

# GC Example

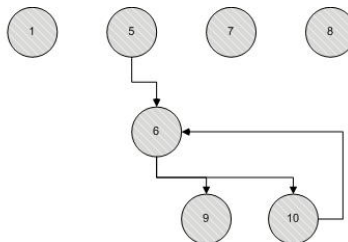
$k(\dots \text{loc}(1) \dots \text{loc}(5) \dots \text{loc}(8) \dots) \text{mstack}(\dots \text{loc}(7) \dots)$



- Continue marking reachable locations
- Locations 9 and 10 both reachable from location 6
- No more reachable locations – 6 is already marked, so we don't loop between 10 and 6

# GC Example

$k(\dots \text{loc}(1) \dots \text{loc}(5) \dots \text{loc}(8) \dots) \text{mstack}(\dots \text{loc}(7) \dots)$



- Finally, GC sweeps unmarked/unreachable locations
- Locations 2, 3, and 4 unreachable, so discarded

# Performance

| Test Case  | GC Disabled |            | GC Enabled |            |             |
|------------|-------------|------------|------------|------------|-------------|
|            | Time (sec)  | Store Size | Time (sec) | Store Size | Collections |
| factorial  | 103.060     | 22193      | 119.987    | 300        | 22          |
| ifactorial | 97.100      | 21103      | 116.811    | 106        | 21          |
| fibonacci  | 401.334     | 76915      | 399.785    | 935        | 76          |
| addnums    | NA          | NA         | 516.023    | 946        | 93          |
| garbage    | 259.500     | 32013      | 147.211    | 20         | 32          |

- addnums and garbage both perform repeated calculations or allocations; other examples are identical to those for SILF
- Store Size is the final size of memory
- Collections is the number of GCs performed



# Evaluation

- GC results mixed: some examples with GC enabled cause reduced performance, others run faster or even allow execution to finish (versus segfault)
- Adding GC required only changes in the memory operations, with no changes in feature definitions
- GC is modular: some operations are generic for all collectors, with specific operations used to interrogate current state and computation (only these are language-specific)

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## Related Work

- Presented work part of rewriting logic semantics project [MeseguerRosu04, MeseguerRosu07]
- Most prior work on performance of rewriting logic definitions has focused on analysis performance, including:
  - Java source and bytecode analysis [FarzanEtAl04b, FarzanEtAl04a]
  - Analysis of KOOL programs [HillsRosu07]
  - Partial order reduction techniques [FarzanMeseguer07]
- Extensive work has been done on garbage collection [JonesLins96], including in pure OO languages [UngarJackson88, UngarJackson92]

# Future Work




- Canonical representations of memory: would use GC, could improve performance
- Further experimentation with GC, other analyses (escape analysis, etc)
- Can Maude be extended with direct support for arrays (or other data structures) that would eliminate need for this work? Would this have drawbacks (in debugging definitions, for instance)?
- GC as a language definition transformation

# Conclusions

- Improved performance of language definitions allows use of more realistic programs during language design
- Changes to shared language modules can improve performance with minimal alterations to feature definitions, can be leveraged across multiple languages
- A stacked memory model like that added to SILF can show significant improvements where it can be used
- Adding GC to languages like KOOL can be done with little additional effort, but has mixed results, improving performance for some programs but degrading it for others

# Questions?

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